

Infrared Thermography in Container Heat Shield Development

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ABSTRACT

This report documents the process of using infrared (IR) thermography for the development of a heat shield for a container in an automotive environment. It discusses the current time-consuming, iterative process of heat shield development using thermocouples and the advantages of using IR thermal imaging cameras for such work, for example, to quantify the effect of important physical parameters such as temperature gradients and air flow across the wall of the container in real time.

Keywords: : Infrared thermography, thermography, heat shield, container.

INTRODUCTION

Automobiles today present many challenges for the engineer. Many systems and subsystems are interconnected to form the complete automobile, meeting all of the requirements of the passenger, comfort, safety, fuel efficiency, costs, etc., all wrapped up in one complete package. The internal combustion engine produces hot exhaust gases, which must be conveyed to the rear of the automobile, often packaged near other systems or subsystems on its way to the rear of the vehicle. While the management of the hot exhaust gases is the primary objective of the exhaust system, other systems need to survive in the same package as the exhaust system in order to perform their primary objective. Extreme duty exhaust system skin temperatures can run up to 2000 degrees F and present a significant radiation heat transfer concern, along with natural convection problems during soak periods. Usually the radiation component of heat transfer from the exhaust system can be minimized quite effectively by the use of a radiation heat shield. While heat transfer targets can be shielded it is recognized that shielding the source rather than the target can be a more cost effective approach on a systems or vehicle level. The challenge is to develop a cost effective shield (either source or target) that minimizes only the radiation that is presenting a problem and to disperse that energy somewhere where it will not create another concern.

Heat shield development presents many challenges. Typically a straight-line approach to isolating radiating heat is used which, due to the conservation of energy theory, only serves to displace heat to other areas. In the past, analog devices (thermocouples) have been used to identify the energy level on the target. This measuring device is a point source and only measures temperature in the area in which it is located; but when a shield is added or changed, the energy is displaced. In order to continue to represent the location of the highest heat energy, the thermocouple needs to be moved. The engineer needs to interpret the energy signature from the data available from the thermocouple matrix and subjectively determine if more definition of the matrix is needed. If more definition is needed then more thermocouples are placed and the test(s) is (are) run again. This process is iterative and time consuming and requires experienced personnel to place the thermocouples accurately.

Due to the nature of a container (thin walled, constant emissivity), infrared thermal imaging is an ideal application for acquiring the energy signature of the container and developing a heat shield scheme around it, being confident that the total energy into the container material is being measured accurately. This paper will describe the development of the use of infrared for the purpose of heat shield development on a polyethylene container.

A typical container packaged in the underbody is shown in Figure 1. For this paper we will look at a container packaged near an exhaust system component (exhaust pipe). The container will be mounted on the body with the exhaust system routed around it. This container will experience all three modes of heat transfer; conduction, radiation, and convection. Energy will conduct into the container thru the mounting hardware from the higher energy level body of the vehicle. Energy will radiate into the container from the higher energy level of the exhaust pipe. Hot exhaust gases from a hole in the exhaust pipe will transfer heat into the container by forced and natural convection. Since the energy level delta between the body of the vehicle and the container is relatively low and the conduction component of heat transfer is miniscule when compared to the radiation and convection component, the conduction component will be ignored in this paper.

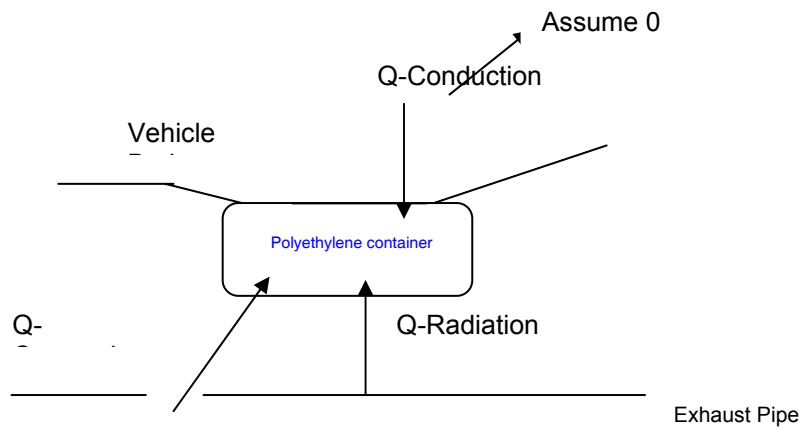


Figure 1. $Q_{total} = (Q_{convection}) + (Q_{radiation})$

LOAD MEASUREMENT

Test Methodology

Due to the nature of a container (thin-walled, homogeneous emissivity), infrared thermography is an ideal application for acquiring the energy signature of the container and developing a heat shield scheme around it, with confidence that the total energy affecting the container material is being measured accurately. The method that was used was to place the infrared camera inside the container (our container was large enough) (see Figure 2).

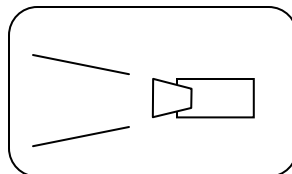


Figure 2.

Infrared thermal imaging radiometers were used to help determine thermal infrared profiles during these tests. These imaging systems measure thermal radiation within a definite bandwidth, over a variable field of view. The data obtained from these measurements can be analyzed to produce a two-dimensional map of apparent temperature called a thermogram. This radiated energy is distributed over a band of wavelengths in the electromagnetic spectrum. Its intensity and spectral distribution is a function of the temperature of the object, so-called black body radiation. Objects at room temperature and other heated objects emit radiation in the infrared region of the electromagnetic spectrum. Thermal imaging systems can greatly enhance the data obtained by conventional contact thermometers because they can produce a spatially resolved map of surface temperatures from the radiant energy emitted in the field of view.

The general radiometric equation was used to convert radiant energy to temperature:

$$\hat{I} = [E_t \times F(T_t)] + [(1 - E_t) \times F(T_b)] - [E_r \times F(T_r)] + [(1 - E_r) \times F(T_b)]$$

Where \hat{I} is the difference in radiance between the target and a reference surface; E_t is the emittance of the target surface, generally unknown; E_r is the emittance of the reference surface, T_t is the temperature of the target surface; T_b is the temperature of background surfaces (i.e., ambient temperature); T_r is the temperature of the reference surface; $F(T_t)$ is the radiance from an ideal emitting surface (i.e., black body) at the temperature of the target surface; $F(T_r)$ is the radiance from an ideal emitting surface at the temperature of the reference; and $F(T_b)$ is the radiance from the background relative to the radiance value from the reference surface when $E_r = 1$. Factors other than temperature determine the emittance of an object. These factors include the type of material, the texture of the surface, the wavelength of the detector, the view-angle, and the temperature of the material. In determining temperatures from the radiant energy from an object, the operator can set the emittance of an unknown target surface to a value of between .01 and 1.0.

VEHICLE TESTING

Containers present a relatively large, constantly and highly emissive surface. The only true challenge is one of packaging. The infrared camera needs to fit inside the container and allow enough flexibility to maintain a maximum 45-degree camera angle to the surface area being examined. Care has to be taken by the thermographer to ensure an accurate reading. The IR cameras we have today allow us to complete this task with minimal damage to the vehicle and future thermal imaging camera technology will give us even more flexibility.

The equipment utilized was a scanner type imager. The thermal resolution is 0.1° C and spatial resolution 1.8 mrad. The sample rate frequency is 50 Hz at minimum. The results were saved on a computer disk and on VHS video tape. The emissivities of the polyethylene container were determined by measuring the temperature of a known gray body surface, referenced to a known black body source and the background of material. Adjustments of the emissivity values for the thermal imager were then corrected to that level, which gave the same temperature of the container to that of the reference material.

We then analyzed the thermograms recorded on the PC disk using thermal image processing software. With this software it is possible to calculate temperatures of various areas, spots, and profiles.

The following images show how the vehicle was set up. An access hole was placed in the vehicle through which the infrared camera was placed in the container. Images were then taken while the vehicle was moving, performing its various tests. Care was taken not to change the operating environment of the container, in particular the airflow characteristics in the underbody of the vehicle where the container is mounted. The hole was sealed up completely around the perimeter to prevent disruption of the normal airflow around the container and to prevent the intrusion of CO or any other noxious fumes into the vehicle passenger compartment. A CO meter was installed to monitor this. The camera was stabilized with an adjustable bracket that was mounted to the vehicle body.

Thermocouples were placed in various locations to correlate the infrared data being acquired. A Fluke Helios Data Logger was installed to monitor and record the analog data.



Figure 1. Test Vehicle: 2000 Saturn LS.



Figure 2. Thermocouple data instrumentation.



Figure 3. Additional instrumentation.

VEHICLE TEST RESULTS

Time Constant Concerns. Because of the relatively low thermal conductivity of polyethylene we would expect to see some amount of time lag (depending on the cross section) for thermal equilibrium to be established between the inside and outside of the container, when subjecting it to a transient thermal condition. The container is being heated on the outside so for a given situation the inside skin temperature maximum should lag in time behind the outside skin temperature maximum. Figure 4 shows the outside ambient and outside skin temperatures and the inside skin and the inside ambient over the cross section of a plastic container. These temperatures were taken during an actual vehicle test. The thermocouples were placed directly opposite one another.

The lower three lines in the chart represent three separate areas, channels 16, 17, and 18, that have been in a thermally stabilized environment for 30 minutes. This shows that, when allowed to stabilize, the outside ambient will tend towards each other and bring the cross section of the container to equilibrium.

The upper three lines in the chart represent the same three areas of the container, channels 16, 17, and 18 in an unstable environment. This part of the test has been run for 12 minutes (the length of one of our tests). The data show that when there is a relatively large delta between the inside and outside ambient, it takes a longer amount of time to reach equilibrium and that a 12 minute test isn't necessarily long enough to allow the system to reach thermal equilibrium. The outside or inside skin temperatures are not necessarily a good representation of the true temperature of the material. An outside skin temperature

can give us a misleadingly high indicator of the material temperature while the inside skin temperature can give us a misleadingly low indicator of the material temperature. When applying maximum design guidelines, however, it is most desirable to use the inside skin temperatures, for this gives us the minimum possible equilibrium temperature that the material will experience. If the container is to melt and thus compromise the integrity of the container, for instance, the entire cross section needs to reach the melting point, not just the outer skin. This phenomenon is exaggerated because of the low thermal conductance of polyethylene.

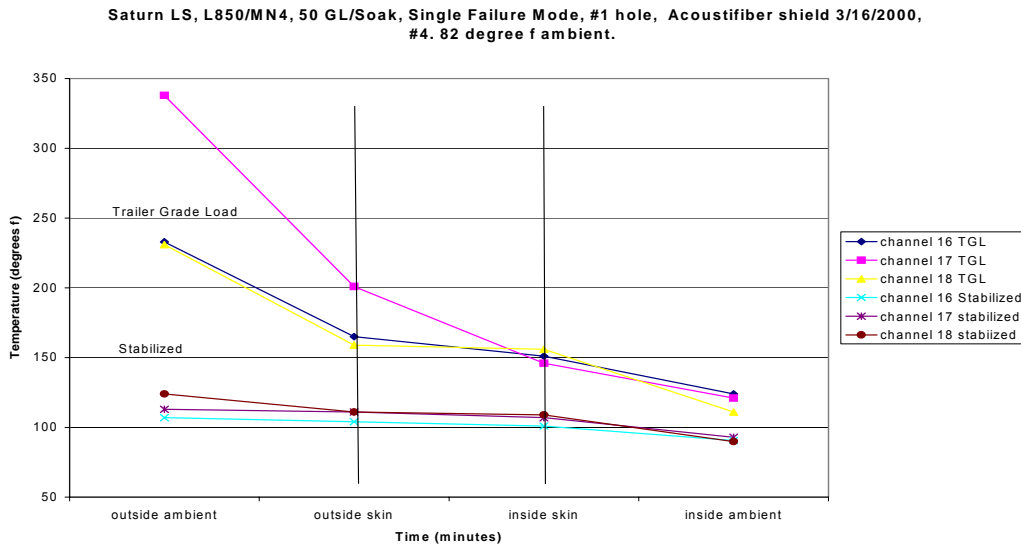


Figure 4.

Figures 5 and 6 are time vs. temperature plots for areas 17 and 18 on a container in a vehicle test. Figure 5 shows that when we get extreme, relatively short duration spikes of outside ambient temperatures, it can drive the outside skin temperatures up considerably but the time is not allowed for thermal equilibrium of the entire cross section of the container. This chart shows a 60 degree F delta between the inside and outside temperatures of the container at the time the maximum temperature on the outside skin is experienced. Figure 6 shows a different area on the container (area 18) that maintains a smaller delta between the inside and outside ambient for a longer time but still produces about a 10 degree F delta between the inside and outside skin temperatures. Thus, if a thermocouple on the outside skin is the only temperature indicator in the system while doing shield development work, then unneeded content and cost could be driven.

Saturn LS, L850/MN4, 50 GL/Soak, Single Failure Mode, #1 hole, Acoustifiber shield 3/16/2000, #4. 82 degree f ambient.

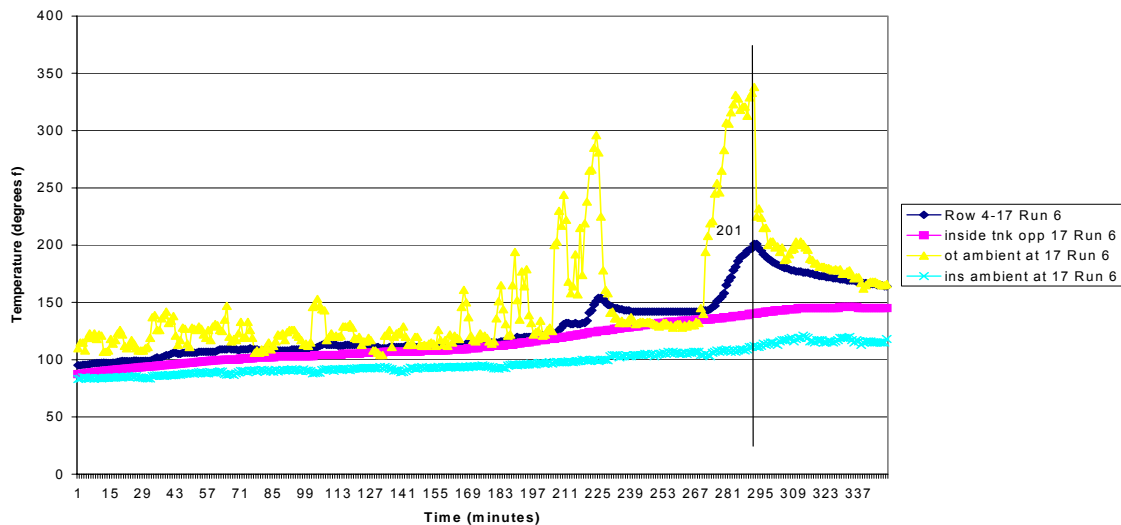


Figure 5.

Saturn LS, L850/MN4, 50 GL/Soak, Single Failure Mode, #1 hole, Acoustifiber shield 3/16/2000, #4. 82 degree f ambient.

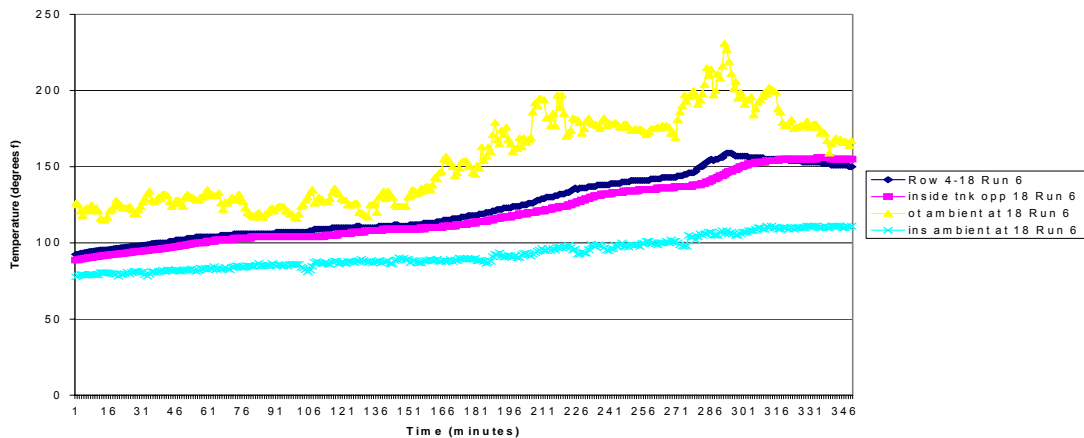


Figure 6.

Data Resolution. Typically, analog temperature measurement devices (thermocouples) have been used to acquire the temperature of containers on an automobile. This would provide us with outside surface temperatures of the container and we would then design a heat energy management system that would not let the outside surface temperature of the container surpass a predetermined temperature design guideline. It is assumed that the design guideline would be conservative enough that a simple, outside surface temperature, single point reading, would provide us with enough information to ensure the integrity of the energy management system design. While this conservative approach to designing an energy management system will suffice, it is both process and product material property sensitive.

Thermocouples are point source devices and thus only give temperature readings for the point at which it is placed. Depending on the material thermal conductivity and cross section, energy can be relatively dispersed or in high concentrations in local areas (hot spots). Automobile underbody containers are sometimes made from polyethylene, which has a relatively low thermal conductivity (k) of 3.2-3.6 btu*in/h*ft²*hr (1010 carbon steel has a thermal conductivity (k) of 37 btu*in/h*ft²*hr).

Thermal Diffusivity, α , is the rate at which energy, in the form of heat, diffuses through a substance.

$$\alpha = k/\rho C$$

As you can see, diffusivity is directly proportional to thermal conductivity, so as we would expect a material such as polyethylene has relatively low thermal conductivity and therefore a relatively low diffusivity rate. The low thermal diffusivity rate of polyethylene means that a high resolution of data is needed to accurately pinpoint the highest temperature location on the container. Figure 7 shows how a 50-mm thermocouple matrix can easily not detect the area of highest temperature when the material has relatively low thermal conductance.

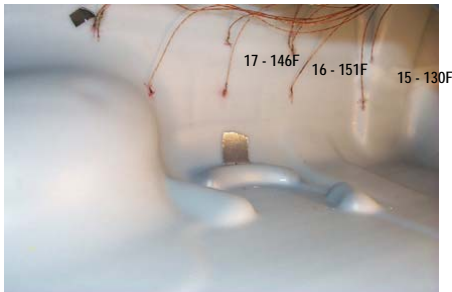


Figure 7.

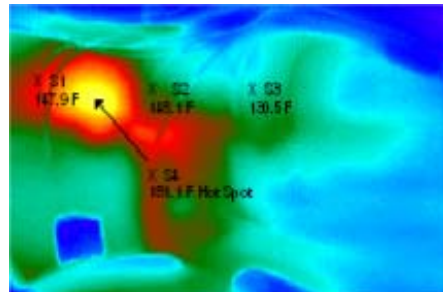


Figure 8.

Figure 8 also shows how the infrared camera readings correlate to the thermocouple readings during an on vehicle test. The visual shows thermocouple readings and the thermogram shows the corresponding infrared readings. In chart form the correlation is:

	<u>T/C</u>	<u>IR</u>
Channel 15	130 F	130.5 F
Channel 16	151 F	148.1F
Channel 17	146 F	147.9 F

Figure 9 shows thermocouples placed on the outside of a container while being heated by a convective heat source as would be experienced by a vehicle container in a failure mode (hole in the exhaust) situation. The thermogram shows the thermocouple wires being heated to a higher temperature than the surface of the container itself. Both on-vehicle and lab data have shown the thermocouple at the end of the wire can give a significantly higher reading (as much as 10-20 degrees F) than the surface of the container just a few millimeters away from the thermocouple location. This problem with thermocouple wires heating up in the convective airstream can be minimized by the careful routing of wires but with infrared thermal imaging it is not a concern.

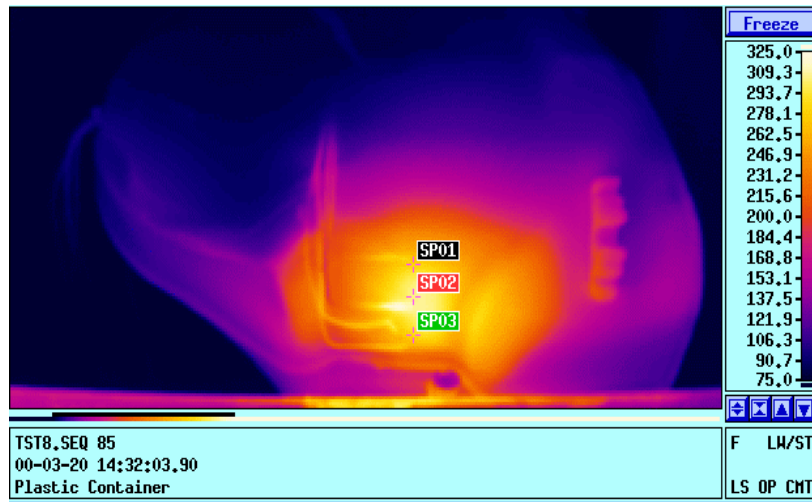
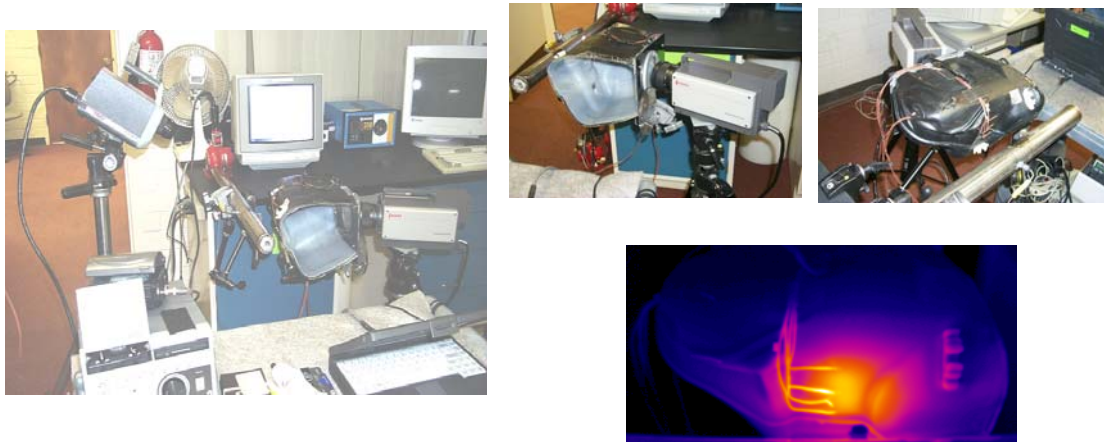


Figure 9.

LAB TESTS

The variability of wall thickness, material thermal conductivity and composition of material plays an important part of the energy transfer into and out of a polyethylene container. An attempt was made to understand, in a controlled laboratory environment, the effects that these parameters have on our traditional methods of data acquisition and our proposed new one.

Lab Setup. In the lab, thermograms were obtained with a computerized infrared imaging system from an Agema Model 900 IR camera containing a single element mercury cadmium telluride detector based on an image resolution of 200 elements by 136 lines at 15 Hz. The scanner is designed to operate in the 8-12 μ band of the infrared spectrum. Figure 10 shows the experimental setup for these measurements. The equations for emission calculation using the above setup are derived from the fundamental radiosity equation.



Infrared External

Figure 10.

LAB TESTS RESULTS

Time Constant Concerns. A closer look at the polyethylene containers used on our vehicles shows that a cross section is actually a number of varying polyethylene alloys (sometimes as many as 6 layers). The outer layer usually has an added pigment for aesthetic reasons. This layering of the material impedes heat transfer through the material. Each layer interface between materials with differing effusivities causes a component of energy to be reflected back to the source. By not allowing an efficient transfer of heat energy, this also contributes to the thermal mismatch between the inside and outside surface of the container.

$$\text{Effusivity, } e = \sqrt{kpC}$$

When two adjacent layers numbered $I + 1$ have different effusivities, energy in the form of heat is reflected at the interface between each layer of material. Figure 11 illustrates this point further. Thus heat transfer through the material cross section is impeded by the reflection of heat at the various layers of the cross section and further contributing to the relatively long thermal equilibrium time.

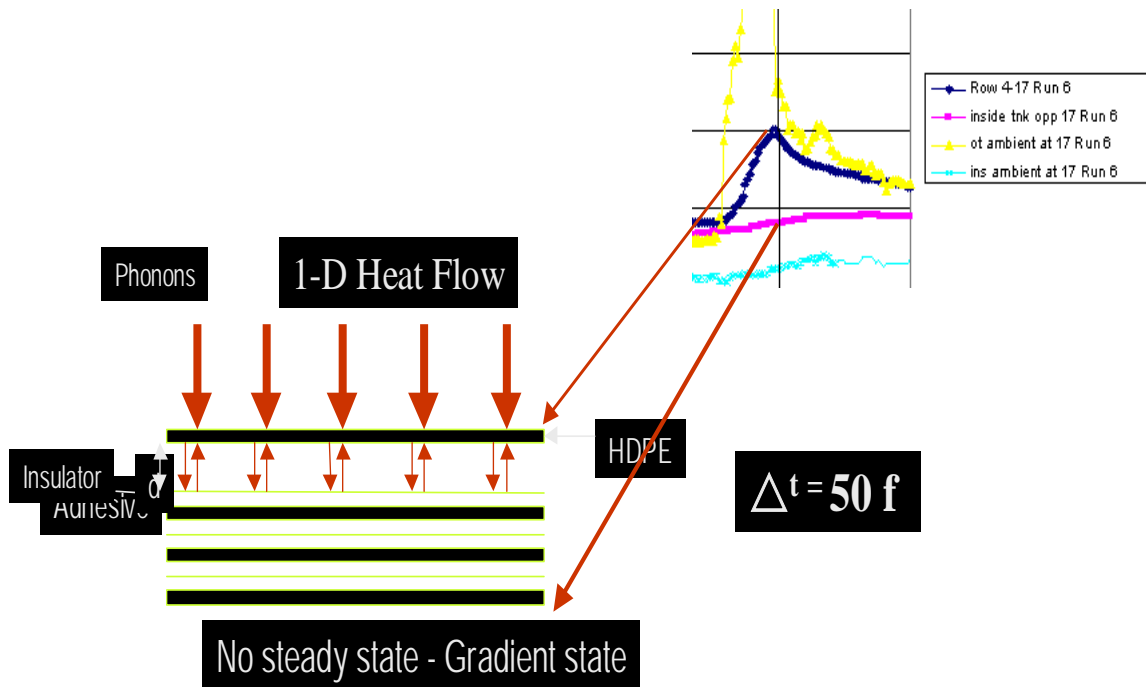


Figure 11.

Figure 12 shows lab data obtained that further illustrate this point. Notice the sharp drop in outside surface temperatures after the heat source was turned off and subsequently the trend towards equilibrium.

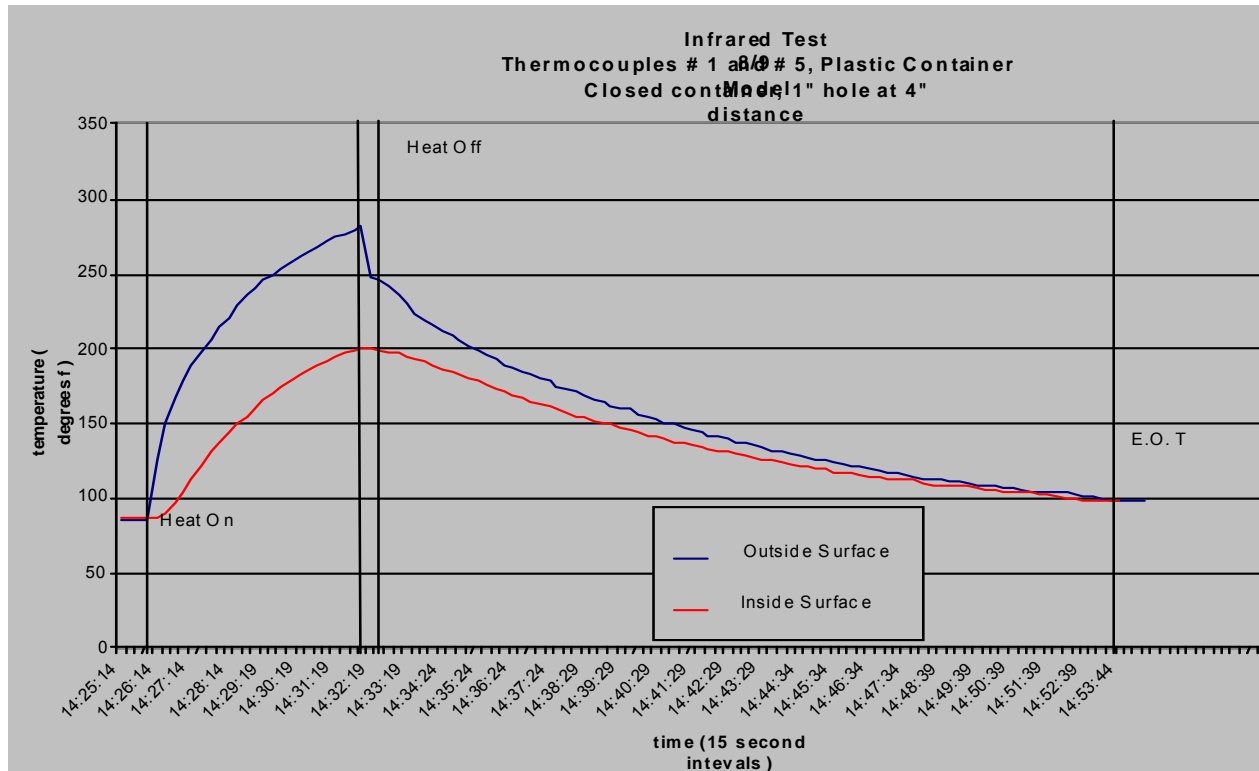


Figure 12.

Thermal Integrity vs. Skin Temperature Measurements. Polyethylene containers have a thermal excursion design guideline of 220 degrees F to 240 degrees F. Figure 13 shows a time vs. temperature chart of a thermocouple placed on a polyethylene container in a lab environment. The container was heated above 400 degrees F for 18 minutes in a relatively local area (about 3 cm dia.). When cooled down, the container showed no sign of thermal degradation and there was no loss of integrity. The med external skin thermocouple was placed on the surface of the container using traditional methods (melting the thermocouple into the polyethylene to about 1mm depth). The OS Skin new style thermocouple was placed near the surface of the container by drilling a hole in the container and inserting it from the inside to the outside skin. The med skin temperature reading was most probably influenced by two phenomena shown in the vehicle data section:

1. The thermocouple wires were in the convective airstream conducting energy down to the thermocouple junction.
2. The low thermal conductivity of polyethylene did not allow the cross section of material to reach thermal equilibrium.

The melting point of polyethylene is between 270 degrees F and 280 degrees F. Why then can we heat a small area to more than twice that temperature and not compromise the integrity of the container? The polyethylene in a molded polyethylene container, both contains the liquid, and provides the structural support for that container. High-density polyethylene (HDPE) is the type of polyethylene used for automotive type containers and is linear in its molecular structure. This means that when the material is heated locally it still has a tendency to hold its structure because the area around it is still rigid and the linear structure is holding it together. If an HDPE container's integrity is to be compromised by elevated temperatures, than a relatively high concentration of heat energy must be directed in a relatively small area. If a large area or the whole container were heated then the tendency would be for the container to sag and/or deform. Of course, this all depends on the amount of heat energy put into the system; any material will experience thermal degradation if the right conditions are met. Temperature can only give us an indication of the thermal integrity of an HDPE container and can not be used as an absolute measurement for it.

Lab test, 85 degree f ambient, 700 degree f exhaust gas, 0.5 inch hole approx. 2 inches from container.

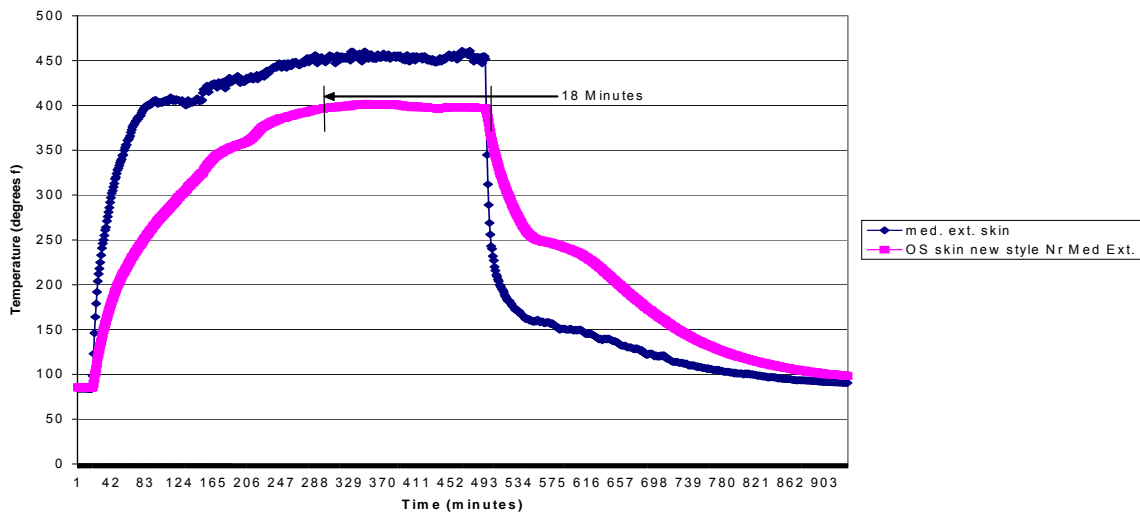


Figure 13.

CONCLUSION

Infrared thermal sensing is the desired mode of temperature measurement for polyethylene containers in automobiles for the following reasons:

1. The high resolution of an IR thermogram allows the detection of localized hot spots that would otherwise be missed using point of contact temperature measurement devices. Even if analog devices are required for validation, infrared thermal sensing used as a placement tool for thermocouples gives a high degree of confidence that the thermocouple was placed correctly.
2. Using infrared thermal sensing eliminates all the problems associated with thermocouples, external wire heating, sensitivity of placement depth, etc.
3. Internal container skin temperatures are a better indicator of thermal integrity and infrared thermal sensing allows for this measurement to be taken in a non-destructive fashion.

Infrared thermal sensing today has packaging limitations that prevent it from being used in many circumstances, however using creative engineering techniques while applying basic thermodynamic principles can help to overcome these limitations and increase the confidence that we have in our data and therefore, our work. This report shows how our old tried and true methods can be, at least complimented by the application of high technology. While we still have needs for the use of thermocouples in container heat shield development, the use of infrared thermal imaging technology increases our confidence that we are getting the right temperature reading in the right location.

When using the techniques described in this paper it is very important to understand the physical properties of the container itself. In this case, with HDPE thermal resistance is very high and thus requires a thorough understanding of the material and the testing process to ensure two things:

1. The temperature that is being measured is the desired temperature, (i.e. inside vs. outside container temperatures)
2. Temperature measured is the correct indicator of what we are trying to understand. In this case temperature is not a complete indicator of failure of the container.

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